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Photovoltaic Power for Space Station Freedom

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Cosmo R. Baraona
Lewis Research Center
Cleveland, Ohio

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PHOTOVOLTAIC POWER FOR SPACE STATION FREEDOM

Cosmo R. Baraona
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

This paper describes Space Station Freedom with special attention to its electric power system. The photovoltaic arrays, the battery energy storage system, and the power management and distribution system are also discussed. The current design of Freedom's power system and the system requirements, trade studies, and competing factors which lead to system selections are referenced. This will be the largest power system ever flown in space. This system represents the culmination of many developments that have improved system performance, reduced cost, and improved reliability. Key developments and their evolution into the current space station solar array design are briefly described. The features of the solar cell and the array including the development, design, test, and flight hardware production status are given.

INTRODUCTION

The Space Station Freedom (SSF) Phase 2 configuration is shown in Fig. 1. It will be a manned, multipurpose facility in low earth orbit (LEO) early in the next decade. It will include four pressurized modules, life support, data, communications, power, and other subsystems along with provisions for experiments and other equipment both inside and outside the pressurized modules. SSF will allow astronauts to live and work in space on a permanent basis. The planned crew size ranges from six to eight people. The operational life of SSF will be indefinite since it is designed to be maintainable and can be resupplied on-orbit.

SSF will be used for astronomical and terrestrial observations and for biological and materials processing experiments in microgravity. Satellites and other space hardware can be repaired and maintained at SSF. It will also serve as a staging base for men and machines traveling to other orbits or other worlds. The capabilities of SSF can grow because power and other subsystems are designed to increase in capability and to adapt to advanced technology to meet additional user and mission requirements. A more detailed description of SSF is given in Ref. 1.

The Phase 1 configuration of SSF (shown in Fig. 2) will be in LEO by 1990. The largest visual

feature of SSF will be the eight photovoltaic (PV) arrays at each end of the main truss. Other parts of the power system that are less visible include the nickel-hydrogen battery energy storage subsystem, the power management and distribution subsystem electronics, and the thermal control subsystem. These subsystems and the structure and other hardware to support them are called the photovoltaic power module (PVPM), which is also shown in Fig. 2. SSF will have four PVPM's and each module has two solar arrays.

Two major differences distinguish the SSF power system from those of previous satellites: size and lifetime. SSF will have an initial Phase 1 capability of 75 kW to the users with over a 250-kW array output at the beginning of life. It will grow to 125 kW after Phase 1 and perhaps to as much as a 300-kW user power ultimately. The SSF system will dwarf typical satellite power systems which are about 3 kW in size. Skylab, America's first space station, generated 12 kW of array power. The Shuttle Orbiter generates 22 kW peak from its fuel cells, but only about 7 kW is usually used. As mentioned previously, the SSF and the power system will have indefinite life with maintenance. Typical satellite power systems are not repairable and have lifetimes of about 7 to 10 years. The evolution of the SSF power system from feasibility through the preliminary design phase is described in Ref. 2.

POWER SYSTEM DESIGN

The electric power system (EPS) consists of the PVPM, the solar dynamic power module (SDPM), and the power management and distribution (PMAD) system. These hardware will generate, store, distribute, and control electric power.

Solar Dynamic

The SDPM (Fig. 3) will be incorporated in Phase 2 of the SSF assembly to enable the power system to grow to as much as 300 kW. Solar dynamic (SD) power is generated by focusing sunlight with an offset parabolic concentrator onto a heat receiver containing a mixture of fluoride salts. A portion of the solar energy heats a helium-xenon gas working fluid and part is stored in the heat of fusion (solid to liquid) phase change of the

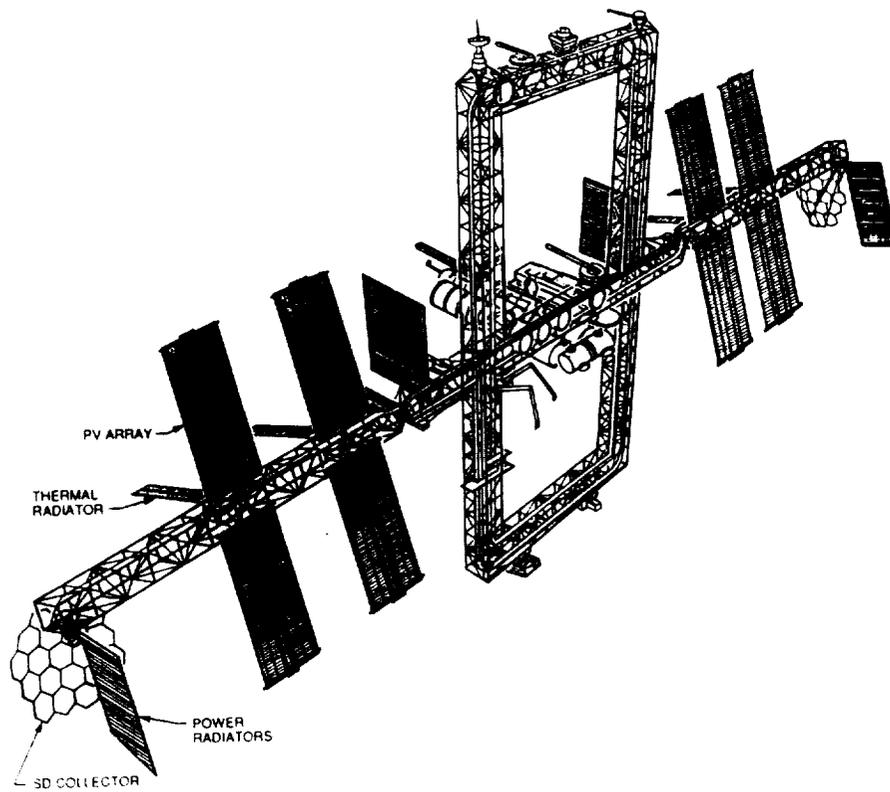


Fig. 1. - Space Station Freedom Phase 2 configuration with PV and SD modules identified

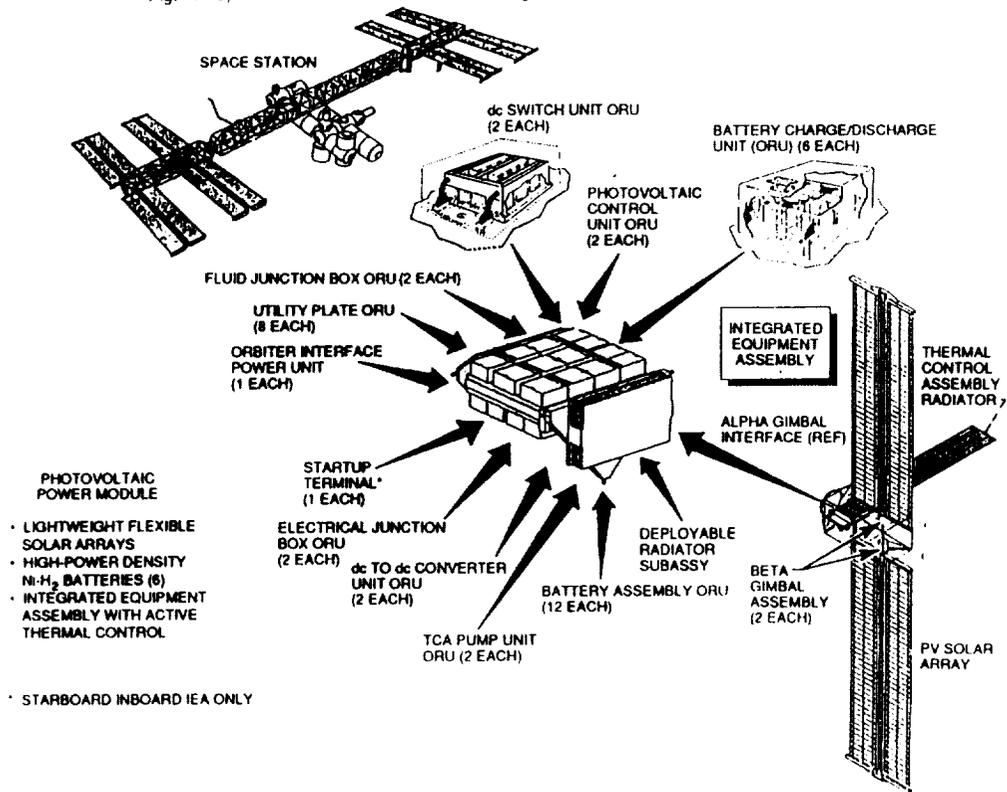


Fig. 2. - Phase 1 configuration and station PV power module

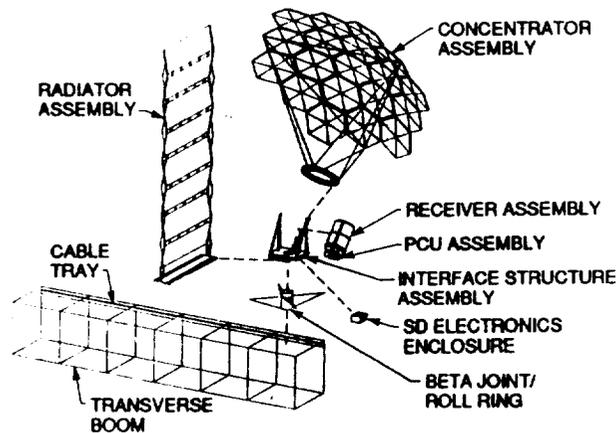


Fig. 3. - Solar dynamic power module configuration.

fluoride salt. The working fluid drives a turbo-alternator in a closed Brayton cycle thermodynamic engine during sunlight and during eclipse. Heat stored in the salt keeps the cycle going during eclipse.

The SD system advantage is low life-cycle cost, due to the smaller surface area of the collector. This smaller area results in less orbit decaying drag and, therefore, lower reboost fuel and resupply costs. The area of the SD mirrors is about one-half to one-third that of the PV arrays. In addition, heat storage in the salt is about 97 percent efficient compared with electric storage in the PV batteries which is about 80 percent efficient. Calculations indicate that the overall sun-to-user efficiency of the SD system is about 20 percent compared with about 7 percent for the PV system, using silicon cells and nickel-hydrogen batteries.

The disadvantages of the SD system are its lack of space operating experience and a sun tracking/positioning requirement more than 20 times more accurate than the PV arrays. The SD mirror requires very fine control methods. Long-term operation of the salt heat storage system, degradation of the mirror optical quality, and heat engine life are additional technical issues for which solutions are being worked on.

Power Management and Distribution

The PMAD system distribution frequency and voltage are key features that determine the EPS system architecture. This architecture has changed several times during the SSF program. Initially, trade studies indicated that a 20-kHz distribution frequency was optimum. Several single-phase transitions were made for primary distribution and secondary distribution. Currently the system primary distribution is 160 V dc. The secondary distribution is 120 V dc. Factors involved in these changes include cost, wire size, weight, power loss, electromagnetic interference and compatibility to power user's system, and experiment requirements.

The PMAD system is designed so that any combination of two failures will not cause a loss of all electrical power. This is accomplished by incorporating redundant switching and controlling units and multiple independent cables to each critical user including the pressurized modules and the various experimental pallet load centers on the station truss.

Control of the EPS will be by semiautonomous local controllers linked to a central controller. This system will monitor and detect faults, isolate malfunctioning circuits, and reconfigure and recover system performance. It will manage and, to an extent, schedule power use to help prevent overloads and to insure full battery charge at the start of each eclipse period.

PHOTOVOLTAIC POWER MODULE

The PVPM shown in Fig. 2 consists of five major components. Two of the components are the sets of two solar array assemblies and sequential shunt units, and the beta gimbals. The beta gimbals are at the base of the arrays and allow one axis sun-tracking as well as rotary power and command signal transfer. (A second sun-tracking axis is provided by the alpha gimbals on the axis of the main station truss.) The sequential shunt unit (SSU) is attached to the base of the beta gimbal. The SSU controls the operation of the array circuits to regulate buss voltage and limit fault currents under certain conditions.

The other three PVPM components include the integrated equipment assembly (IEA), the thermal control system and radiator, and the truss structural elements. The IEA supports numerous boxes called orbital replacement units (ORU's). The IEA provides electrical and thermal control utilities to each ORU. There are several different types of ORU's including battery assemblies, battery charge/discharge units, direct current (dc) switching units, dc-to-dc converters, power distribution and control units, junction boxes for fluid and electrical services, and thermal control system pump units.

The solar array power is regulated to the primary distribution voltage (160 V dc) by the SSU's. The power is then transmitted through the beta gimbal by roll rings to dc switching units. During sunlight, a portion of the array power charges the nickel-hydrogen batteries. This energy is discharged during eclipses to power the station. This process is controlled by the battery charge/discharge unit. The primary 160-V dc voltage is converted to the secondary distribution voltage of 120 V dc by dc-to-dc converter units for distribution to loads throughout the station. PV controllers manage the PV power module functions.

Nickel-hydrogen (NiH₂) batteries consisting of 81 amp-hr cells are used for eclipse power. They allow high power levels with low weight. Nickel-hydrogen cells have been flight proven for many geosynchronous (GEO) spacecraft. They have good discharge characteristics and provide inherent

overcharge protection. The space station program is testing NiH₂ cells for LEO conditions where the number of eclipse and thus charge/discharge cycles is much higher than in GEO. These cycles result in an internal pressure change within the cell between 900 and 600 psia which strongly influences the life of the battery. A nominal 35-percent depth of discharge is used to provide 5-year battery life.

Solar Arrays

PV arrays (Fig. 4) generate all the power for the Phase 1 SSF. They are being designed, built, and tested by the Lockheed Missiles and Space Company in Sunnyvale, California. Each array is approximately 118 by 39 ft (36 by 12 m) and weighs approximately 2200 lb (1000 kg). At the beginning of life in the best orbital conditions, each wing will produce about 32 kW; in the worst case orbital conditions, about 24 kW after 15 years. This electrical performance includes the degrading effects of low earth orbit radiation, on-orbit operating temperature, and system losses such as wiring resistance and series circuit matching losses. Degradation losses due to thermal cycling, micro-meteoroids, plasma interaction effects, ultraviolet (UV) radiation, contamination due to the local environment around SSF, and solar intensity

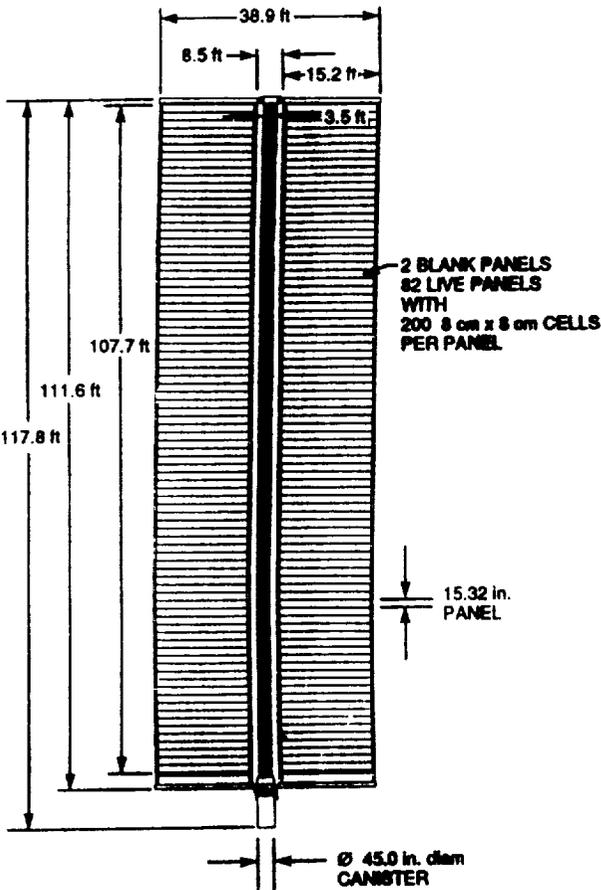


Fig. 4 - Space Station Freedom solar array deployed configuration.

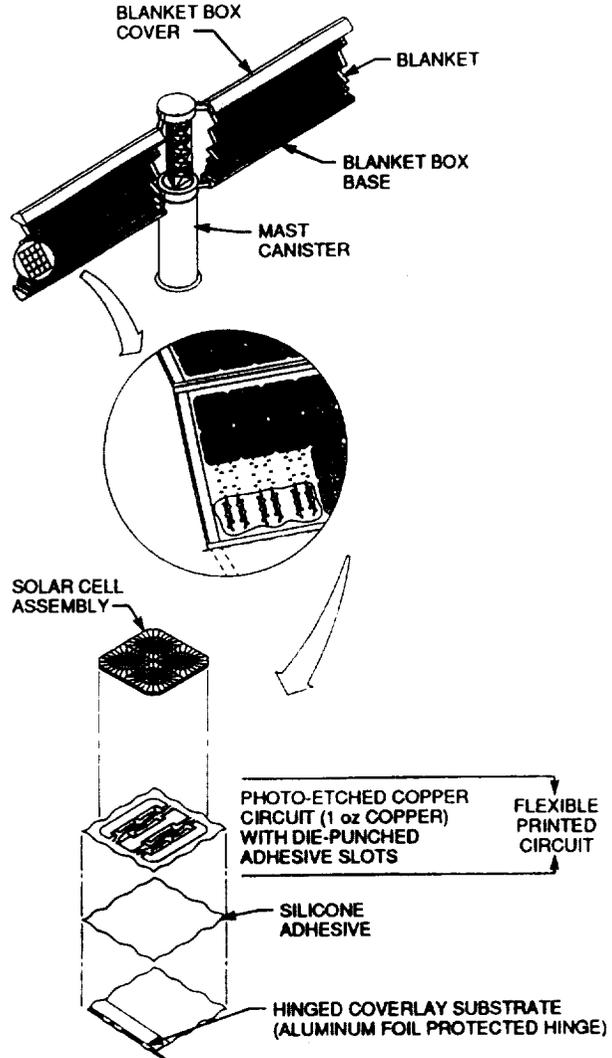


Fig. 5 - Space Station Freedom panel.

variation due to orbital variation are also factored into the performance predictions.

Each wing consists of two lightweight blankets, and each blanket contains 84 hinged panels (Fig. 5) which fold accordion-style for launch. There are 82 live panels and 2 dummy panels. One dummy panel (i.e., no solar cells) is located at each end of the blanket nearest the containment boxes where partial shadowing will occur. Each live panel consists of 200 large-area silicon solar cells wired in series. The series connections are accomplished by copper traces imbedded between two sheets of 1-mil-thick transparent polyimide which form the panel substrate. Each eight-cell-series string has a bypass diode wired in parallel. This diode limits power losses caused by transient shadowing and open circuits due to broken cells or interconnects. The edges of adjacent panels form loop-type piano hinges. Two adjacent panels (400 cells) are wired in series to form a circuit with a nominal output of 160 V dc. Each wing

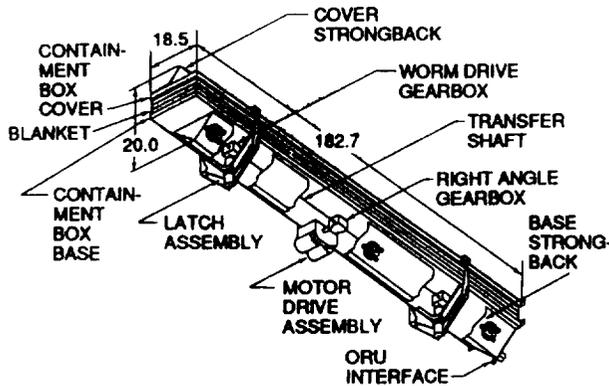


Fig. 6. - Space Station Freedom containment box isometric drawing.

consists of 164 live panels which form 82 circuits. The panels are connected to a flat conductor cable at each edge of each blanket. This cable carries the power to the base of the array.

The folded blankets are contained in boxes (Fig. 6) for protection during launch. The panels are compressed by latch and preload mechanisms to prevent solar cell damage due to launch vibration and acceleration forces. Motor drive assemblies release the latches and allow the boxes to be relatched when required. The two-blanket containment boxes are attached to the top of a mast canister which contains a foldable articulated square truss (FAST) mast. Motor drives deploy the FAST mast, and the mast pulls the folded panels out of the blanket boxes to deploy and tension the array on orbit. During launch the mast is stored in its canister and the containment boxes are arranged side by side for minimum packaging size in the cargo bay of the Orbiter. Further details on the array design are given in Ref. 3.

The solar cell design selected for SSF is an 8 by 8 cm, 8-mil-thick silicon device with wrap-through contacts. It is 10-ohm-cm, p-type base resistivity with a shallow phosphorous diffused n-type junction and with a boron back surface field. Significant features of the cell are its wrapthrough front contacts and gridded back contacts. The front collector grids converge on four round insulated holes in the cell. The front metallization wraps through these holes to allow n contact interconnection on the back of the cell. The back contact is gridded to allow transmission of infrared (IR) light that is not absorbed by the silicon. In conventional cells with full coverage back contacts, the IR is absorbed in this metallization and causes heating which reduces cell voltage and power output. The IR energy coming out the back of the cell is also transmitted through the transparent panel substrate. Thus the array operates at a lower temperature with higher voltage and power output.

Another benefit of wrapthrough contacts is that both the n and p connections of the cell to the copper circuit can be done in one operation from the back side of the cell. This significantly

reduces array panel assembly time and cost. The interconnection of the cell silver contacts to the copper traces in the panel substrate is accomplished by semiautomated parallel gap welding. These interconnects have demonstrated a 15-year lifetime in a simulated LEO thermal cycling environment.

At the time of this writing, the array blanket components are in various stages of design. The solar cells have undergone preliminary and critical design reviews. Flight-type cells have been produced at two vendors: (1) Applied Solar Energy Corp. and (2) Spectrolab Inc. Balloon flight calibrations have also been performed. Qualification testing is in progress. A total of over 265 000 flight-type cells will be required.

The bypass diode has had its preliminary and critical design reviews. Production of about 33 000 diodes is planned after qualification testing at Advanced Optoelectronics. The panel preliminary design review is complete, and detailed design is in progress. Over 1344 panels will be produced by Lockheed. Other array components are in the preliminary design stage including the containment box, the FAST mast, and other array mechanisms. Development tests and thermal, structural, and fatigue analysis are in progress. Extensive qualification and acceptance level testing at the component, coupon, panel, ORU, and assembly levels is planned.

Array Design Heritage

The design heritage for the solar array traces its roots to research and development programs which began in the 1970's. These programs included the solar electric propulsion stage (SEPS) for interplanetary missions. SEPS incorporated a lightweight, high-performance solar array using 2 by 4 cm wraparound contact cells to supply power (4). This array concept is the foundation on which the current space station array design is based. The SEPS program built a demonstration single-blanket wing which was later upgraded to the solar array flight experiment (SAFE). SAFE was successfully flown on the space shuttle in 1984 and demonstrated the array packaging concept. It also provided data on array structural dynamic behavior in zero gravity (5). In the early 1980's, the SEPS array design was proposed as a primary power source for the shuttle orbiter in the power extension package (PEP) program. PEP studied the adaption of the SEPS interplanetary array to the LEO environment, including the effects of thermal cycling on solar cell interconnects. PEP developed and demonstrated pilot production of a 6 by 6 cm wrap-around contact cell as a means to lower cell and array assembly costs through reduced piece parts handling (6).

After the first shuttle flights, the damaging effects of atomic oxygen (AO) in LEO were discovered. Atomic oxygen attacks certain spacecraft and solar array materials and poses a threat to hardware survivability for long-term missions. In the mid-1980's, the space station program initiated

a development contract called photovoltaic array environmental protection (PAEP) to protect or replace array materials subject to damage by AO. The PAEP contract has developed and demonstrated coatings that successfully withstand the effects of AO (7). These protective materials can be applied in large-scale processes and are compatible with all array manufacturing and handling steps. Small materials samples and limited scale flight tests are planned. Preliminary results from the recently retrieved Long Duration Exposure Facility are encouraging and give confidence in the AO protection methods.

The PAEP contract has also provided protected array panel coupon segments and full-scale panels. The coupons have been thermally cycled to simulate LEO temperatures. They have successfully survived 15 years (87 000 cycles), a key requirement for the welded interconnects and the thin-panel substrate (8). The PAEP panels were used in a test that simulated the LEO space plasma environment to determine the interaction of the electrically active panel with the plasma. No significant parasitic currents or arcing events were detected under normal operating conditions (9).

CONCLUSIONS

The electric power system is vital to the success of Space Station Freedom. Few of Freedom's research and exploration missions can be accomplished without reliable electric power. The current EPS design meets system requirements in a safe, cost effective manner. It incorporates a blend of flight-proven PV modules and promising high-performance SD modules linked by the PMAD system.

The PV arrays and solar cells used on Space Station Freedom represent the product of numerous advances in array and cell design as well as advances in understanding the operational environments. These advances resulted from many research and development activities throughout the 1970's and 1980's - only a portion of which have been mentioned in this paper. The photovoltaic community can be proud of a job well done in providing Space Station Freedom, the largest space PV system ever, with lightweight, flight-proven designs, and manufacturing capability. More advanced cells and array designs being developed today extend the state of the art beyond that of silicon cells and arrays. With continued development, these new designs will provide the space station with

opportunities for PV power system growth and technology evolution into the 21st century.

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